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# Assessing the energy efficiency improvement potentials of HVAC systems considering economic and environmental aspects at the hospitals

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ABSTRACT

The energy use in the world is increasing significantly owing to increase in per capita consumption of energy and growing population. Due to increased energy demand and the depletion of existing fossil fuel based sources, it is required to use the energy more efficient. Researches show that, hospitals represent approximately 6% of total energy consumption in the utility buildings sector. Heating, Ventilation and Air Conditioning (HVAC) systems are the major part of electrical energy consumption at the hospitals. In this paper, the research papers and practical studies on energy efficiency and energy saving potentials on HVAC systems at the hospitals are presented. Under the following sections, the latest literatures including research articles, conferences, e-books, handbooks and company reports interested in energy efficiency, energy saving and energy management HVAC systems are summarized. Variant Refrigerant Flow (VRF) technology enables greater energy efficiency and cost savings compared with traditional HVAC systems is also introduced. This detailed review also focuses on the payback periods of some projects on HVAC including the installation of cogeneration, trigeneration, chiller, new burners, heat exchangers and steam trap systems.



**Contents**



## 1. Introduction

Researches focused on energy efficiency, saving potentials and energy management show that the hospitals represent 6% of total energy consumption at the utility buildings sector [1]. Utility buildings are large space offices, shops, hotels, restaurants, educational establishments and health-care facilities. HVAC system is the single largest energy consumer in these types of buildings. It accounts for almost 60% of total energy cost in a building [2]. The energy consumption distribution of a hospital can be classified by electrical energy consumption types. HVAC (especially cooling and ventilating) systems are the major part of electrical energy consumption. If the absorption chiller is not in use, then the air-conditioning system is responsible for around 70% of total electricity consumption [3].

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Among them, the chillers, the chilled water pumps and the fan of the cooling towers would need 43.94% of the total electricity [3]. The use of energy efficient electric motors and variable speed (frequency) drive (VSD) systems are the best and most cost effective ways to reduce total electrical energy consumption especially in HVAC system at the hospitals. HVAC systems provide conditioned air (cooling, ventilation, thermal comfort and humidity control) to the people and locations in the hospitals, airports, industrial districts and large space buildings. HVAC systems control temperature, humidity and air quality inside the buildings and locations. They are generally used in large office buildings or climate controlled places such as hospitals, offices, hotels and government buildings. In this paper, the central HVAC system with water cooled chiller is focused instead of the individual systems. Central system is an air conditioning system which uses a series of equipment to distribute cooling media to exchange heat and supply conditioned air from one point (e.g. plant room) to more than one room [2]. Central HVAC system consist of heating unit comprise of boiler, ventilation unit comprise of fans and cooling unit comprise of chiller as shown in Fig. 1 [4]. Heating function is commonly used in cold climates and cooling function is commonly used in warm and hot climates. Air conditioning means removal of the indoor air humidity. In the medium or large buildings, central HVAC systems

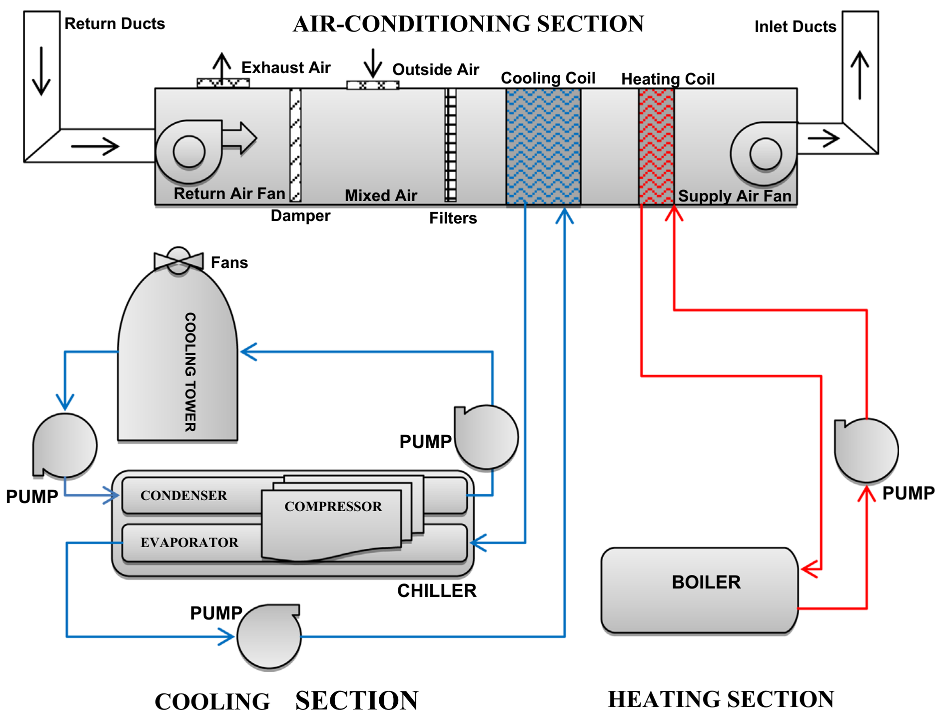


**Fig. 1.** Schematic diagram of the conventional HVAC system.

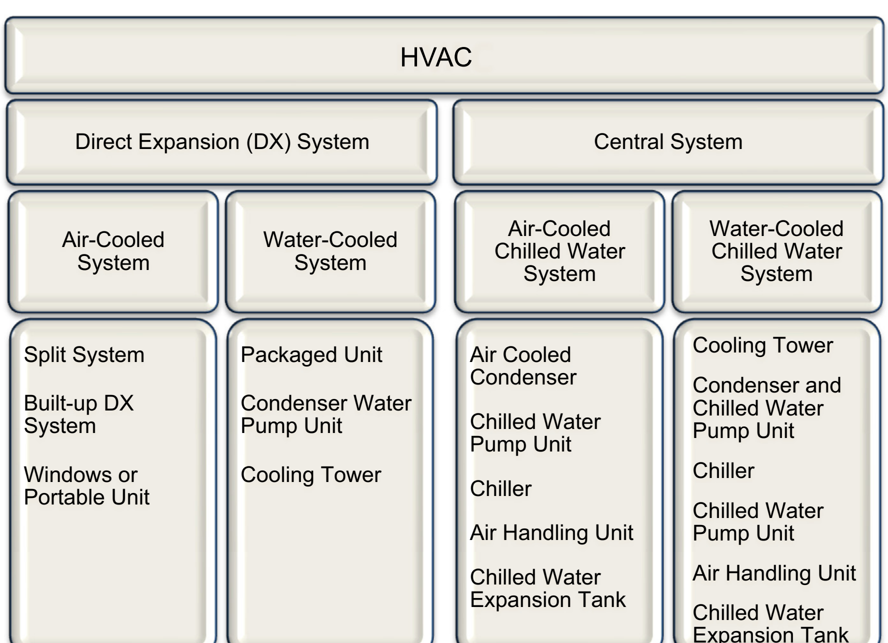


**Fig. 2.** The classification of HVAC system.

are generally used but in the small buildings such as houses, direct expansion system such as split system is preferred.

HVAC systems are divided into two parts namely direct expansion (DX) and central systems as shown in Fig. 2 [1]. DX systems use the refrigerant directly as the cooling media. The refrigerant inside the evaporator absorbs heat directly from the air used for space conditioning. Central system is an air conditioning system that uses series of equipment to distribute cooling media to exchange heat and supply conditioned air from one point to more than one room. According to the type of condenser used, DX system is either air-cooled or water-cooled systems and similarly, the central air-conditioning system is either air-cooled or water-cooled system. Air-cooled and water-cooled systems are categorized by their capacity and efficiency. In the literature, there are many papers on HVAC systems. Balaras et al. [5] reviewed published standards and guidelines on design, installation, commissioning, operation and maintenance of HVAC installations in hospital operating rooms, indoor thermal conditions and summarized measured data from short monitoring of indoor thermal conditions along with audit results and main characteristics of 20 operating rooms in 10 major hospitals. The commonly faced problems are insufficient indoor air exchange, poor control on indoor thermal conditions, bad space ergonomics that influence the ventilation system operation, poor technical installations maintenance and understaffed technical departments. According to international regulations and standards, the desirable indoor air temperature is usually 20–24 °C and the recommended levels of indoor relative humidity are between 30% and 60%. Most of the standards recommend 20 ACH (Air Change per Hour) to obtain 50–150 colony forming units (CFU)/m$^3$ of air. After the measurements, they have identified the problems of HVAC systems and given some advices to mitigate these problems. They have advised regular maintenance and the sealing operable windows in the older buildings. In addition, pipe penetrations and joints should be tightly sealed. The layout of objects in room is important for HVAC systems. Objects close to the radiators or blowers of fan should be moved the free space. According to different conditioning spaces, hospitals should be divided to zones and different air handling units (AHUs) should be used for every zone. Finally, they advise that the hospitals should be controlled by officials.

Research conducted by Ahmadzadehtalatapeh and Yau [6] studied the effect of heat pipe heat exchangers (HPHXs) on the existing air conditioning system of a hospital ward located in Malaysia, a tropical region. Fieldwork study showed that the existing air conditioning system operating in the Orthopedic Ward, University of Malaya, Malaysia is not capable of providing the desired supply duct air and indoor air to the space. Therefore, the possibility of improving the air conditioning system by adding HPHXs was investigated. The impact on energy consumption, power savings, supply duct air and indoor air with HPHXs incorporated in the air conditioning system were simulated and the results were compared with the existing system. Based on the present research work, the system with the added eight-row HPHXs is recommended to provide convenient and healthy air into the ward space according to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommendations. The simulation results for the entire year show that the new system makes it possible to save a total amount of 455 MWh by using the eight-row HPHXs in the system. The research also showed that by considering the cooling equipment efficiency and tariff rate for power in Malaysia, a total amount of $42,227 could be saved annually with the application of the eight-row HPHXs in the ward air conditioning system. Moreover, it was found that by recovering the energy in the AC system, the eight-row HPHXs retrofit would pay for itself in 1.6 years.

Khodakarami and Nasrollahi [7] investigated literature reviews of thermal comfort in hospitals that have been published until 2012. In addition, they investigated the direct effect of thermal comfort on health. They accepted that thermal comfort as a parameter of indoor air quality in hospital affects the working conditions, wellbeing, safety and health of the medical personnel who work in these environments. Although different research is undertaken on thermal comfort for patients in hospitals, it is also necessary to study the effects of thermal comfort conditions on the quality and the quantity of healing for patients in hospitals. Thermal comfort variables can change, based on different conditions of patients, the different activities of staff, the different types and numbers of equipment. To solve this problem the best recommended option is to prepare different thermal zones based on different temperature and air velocity for different thermal comfort requirements. Their study finally concluded that it is important to find some solutions to reconcile the different thermal comfort conditions required by different occupants in hospitals. According to their opinions, their solutions could be used whenever patients and the attending caregivers have to stay in one room for a long time compulsorily.

Air volume in the building is important for the livings. Kim and Augenbroe [8] evaluated the adaptive variable air volume (VAV) operation over the current practice of the VAV that is set to constant air volume. The adaptive VAV temporarily increases the volume offset before the door is opened and thus induces a higher negative pressure differential. Congradac et al. [9] performed a study to increase energy efficiency in hospitals, using a variety of currently available technologies. Congradac et al. [9] concentrates on the creation of a mathematical tool for the exact calculation of room/building energy demands. A prerequisite for the determination of savings is the accurate calculation of energy consumption and then the application of different methods of intelligent control for the energy savings, which should be combined with a system of expert advices in order to gain the highest efficiency.

Research conducted in Dascalaki et al. [10], indoor conditions in Hellenic operating rooms (ORs) were monitored and data were used to assess the exposure of medical personnel to anesthetic gases and other indoor chemical compounds. Measurements were performed in 17 ORs at 9 hospitals. Even though mechanical ventilation and active scavenging systems were employed in the audited ORs, medical personnel are still exposed to poor indoor air quality as a result of various gaseous compounds encountered. Yau et al. [11] focused on the ventilation of multiple-bed hospital wards in the tropical climate, taking into account the design, indoor conditions and engineering controls. The required indoor conditions such as temperature, humidity, air movements and indoor air quality in the ward spaces are summarized based on the current guidelines and practices. Recent studies and engineering practices in the hospital indoor environment are elaborated. Usage of computational fluid dynamics tools for the ventilation studies is discussed as well.

Measurement and monitoring of energy consumption is very important. Chen et al. [12] proposed practical predictions of hospital air-conditioner electricity using the artificial neural network, owing to its excellent predict ability. The influence variables of hospital air-conditioner electricity are included temperature, relative humidity, the previous 1 hour electricity, the time in day and some uncontrolled variables, e.g. the number of surgical operations, the number of persons; and some fix variables. Chen et al. [12] obtained the results that the weekday load model is better than whole day model to acquire the optimal load forecasting of air-conditioner. According to Chen et al. [12], the results not only be referred to control the operation for air-conditioner system, but also to forecast the hot water production with the reheat system in hospital. The focus of the study performed by

Esmaeili et al. [13] is to estimate the overhead energy consumption of healthcare facilities where buildings are open and operating 24 h a day/365 days a year. In Esmaeili et al. [13], 3 different methods for estimating overhead energy consumption of the CT and X-ray rooms in the radiology department of a hospital: a heuristic using annual energy consumption, thermal analysis and simulation were investigated and compared. The comparison of methods will provide information and guidance on the selection of a method with a given level of accuracy and ease of application.

Air curtains are also useful when it is wished to separate two contiguous areas while permitting traffic of people, vehicles, materials or objects between the two separated zones. Diffusion and transport of heat (hot or cold temperatures), moisture, insects, dust, smoke, pollution, particulate matter and odors between the two areas separated aeraulically in this manner can thus be kept to a minimum. The efficiency of such devices ranges from 60% to 85%. Air curtains are commonly used at the entrance of volumes presenting only one opening to the outside (a room and its door) to preserve prescribed climatic conditions in this volume. The use of multiple gaseous barrier systems to sustain given climatic conditions (in the broadest sense of the term) within a given domain is rather new [14].

The paper is therefore organized as follows: After this introductory section, the cooling systems of HVAC are discussed in Section 2 and the heating systems of HVAC are presented in Section 3. VRV/VRF systems are discussed in Section 4. The basics and applications of cogeneration and trigeneration systems at the hospitals are discussed in Section 5. Different studies on cooling and heating systems are presented in Section 6 with practical projects. And finally, the main points and significant results of the study are summarized in conclusions.

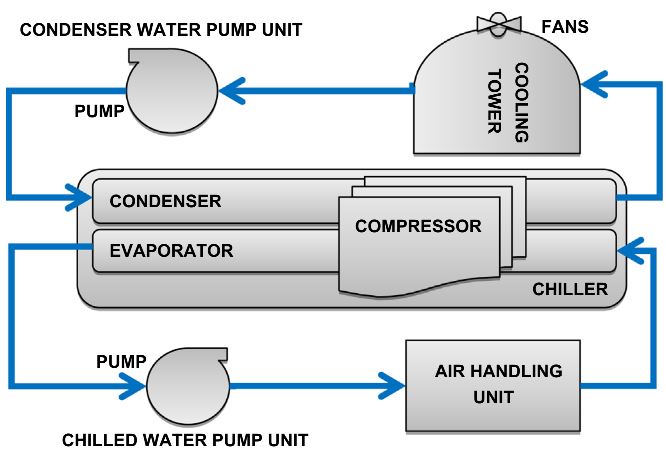


**Fig. 3.** Schematic view of a cooling system.

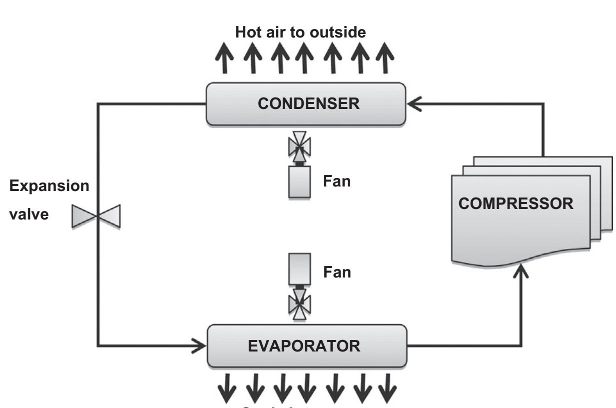


**Fig. 4.** The operation principle of the chiller.

## 2. Cooling systems of HVAC

Different cooling systems are used in hospital, industry and other sectors. One of the cooling systems in HVACs is shown in Fig. 3. The operation principle of the cooling system is very simple. The cooled water in the cooling tower is sent to condenser by condenser water pump. Condenser converts steam with water which is named as vapor to liquid. Compressor is used to pump this liquid in the cooling system. It is also used to compress gases refrigerant in the system. Compressor can be though the heart of the cooling system. The vapor is pumped from evaporator by compressor. The main functions of a compressor are to pump refrigerant through the cooling system and to compress gaseous refrigerant in the system. Air handling unit is used for air conditioning. Fan coiled unit is used instead of AHU for smaller systems.

The main component of cooling system is chiller that mainly consists of evaporator, condenser, compressor and expansion valves as shown in Fig. 4 [15]. Chillers are the largest consumer of energy in the cooling systems. The main duty of a chiller is to process vapor compression and vapor absorption via condenser and evaporator. Evaporator is used to evaporate refrigerant liquid and then gas form is occurred. Compressor with the refrigerant gases cools the water in evaporator. Heat is generated while the water is cooling. The generated hot air is sent to condenser. Condenser is used to condense vapor to liquid. The generated new hot liquid is sent to cooling tower with the pumps. Condenser can be classified into two major types, air cooled and water cooled. There are advantages and disadvantages sides of two systems against each other. For example, at the place that has no water, the chiller with air cooled condenser should be preferred. Similarly, at the very cold climate as continental climate, air cooled systems are preferred because water freezes at 0 °C. If all climatic conditions are satisfied, water cooled condenser is preferred in large buildings and air cooled condenser is preferred in the smaller buildings (i.e. single house or small office) or the places having no enough space.

In cooling systems, it does not matter whether the system is air cooled or water cooled. According to requirements, the structure of building and climatic conditions, the selection is performed. According to electricity consumption, when the cooling section in HVAC systems are investigated by considering energy efficiency, chiller group, pumps and fans should be especially focused. According to Federation of European Heating, Ventilation and Air-conditioning Associations (REHVA), Chillers' sales by construction type are 69% air cooled non-ducted, 25% water cooled, 4% water cooled ducted and 2% condenserless. By applying an

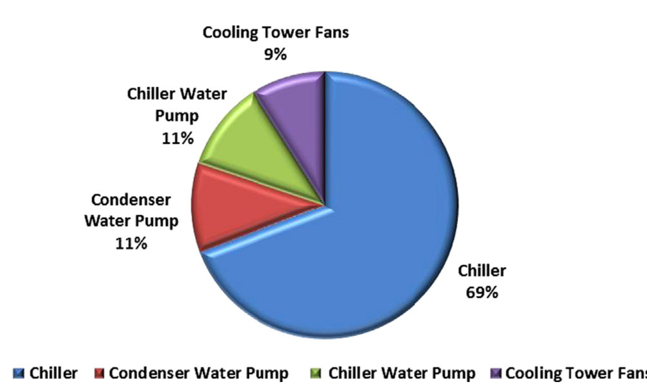


**Fig. 5.** Equipment energy use by percentage of chiller system at full load.

efficient design concept, selecting efficient components and controls and commissioning the system, it is possible to produce a chiller plant that uses 30–50% less energy than a system designed (Chillers 39% savings, pumps 65% savings, cooling towers 40% savings) [16]. The energy usage percentages of chilled water system at full load are shown in Fig. 5 [17]. A neglected or poorly maintained cooling tower can reduce chiller efficiency by 10–35% and a dirty coil condenser of an air cooled chiller as much as 5–15% [18]. Chemical cleaning of the inside of the condenser and evaporator heat transfer surfaces can result in a 5–10% energy savings–kw/ton [18].

The selection of cooling materials used in cooling system is very important. Zhai et al. [19] reviewed the previous works on phase change cold storage for air-conditioning systems focusing on two aspects including phase change materials (PCMs) and applications. According to studies on PCMs, the first step is to composite PCMs to achieve an appropriate phase change temperature. The second step is to change the structure of PCMs by adding nanoparticles or by packaging the materials with capsules or porous medium in order to achieve desired thermo physical properties. Based on the existing researches, the technology of PCM storage seems to be practical in solar air-conditioning systems, latent cooling storage and transport systems, mixed cold storage air-conditioning systems and some other novel air-conditioning systems. Hatamipour et al. [20] was designed to estimate the cooling load power consumption during the summer in the hot and humid areas of Iran. The actual electrical energy consumption for the cooling systems of some typical buildings including a city hospital in a hot and humid region in South of Iran was recorded during the peak load period of the year (July–August). The records were used for estimating the total power consumption of the cooling systems in this region. The cooling systems power consumption in this region accounted for more than 60% of the total power consumption during the peak load period of the year. A computer program was developed for simulating the effect of various parameters on cooling load of the buildings in hot and humid regions. According to the simulation results, use of double glazed windows, light colored walls and roofs, and insulated walls and roofs can reduce the cooling load of the buildings by more than 40%. To enhance clean room energy efficiency, a new methodology is proposed in Su and Yu [21] to determine the proper chilled piping pressure setpoint for the pumps. Test results showed that, with their method, the proper differential pressure setpoint for chilled water pumps with VSDs could be effectively determined. The results also indicated that, by using the new setpoint obtained from the proposed approach, the percent energy savings would be in the range of 42–53%, depending on the existing setpoint and pipeline data. The investment benefit of new or planned pumps would be about 43–81% due to taking a proper setpoint into account.

## 3. Heating systems of HVAC

The main component of heating system is a boiler. Boiler is a member of the pressure vessel class and can be classified into different types, according to temperature, pressure, capacity, burner types etc. Boilers are designed to produce steam and obtain hot water. Produced hot water in a boiler is sent inside the buildings via steam pipelines. Collectors are used to prevent the pressure losses at the pipelines. Collector points are placed in the buildings and deliver the steam to other locations. In a boiler, combustion affects the energy efficient directly. Burner is a device which is used to perform combustion. There are some important factors such as supplied air, mixing of air and fuel, temperature and combustion time for combustion. A typical heating system is shown in Fig. 6. Approximately 40% of all commercial buildings use boilers for space heating. 65% of the boilers are gas fired, 28% of the boilers are oil fired and 7% of the boilers are electric [22]. The combustion efficiency of older boilers is generally between 65% and 75%, although inefficient boilers can have efficiencies between 40% and 60% [23]. Energy efficient gas-fired or oil-fired boiler systems can have efficiencies between 85% and 95% [23].

Heat pump installations increase energy efficiency day by day in HVAC applications. Energy efficient cooling at Aarhus University Hospital in Denmark was realized by Danfoss Group Global. Aarhus University Hospital replaced a huge amount of old decentralized cooling units with one, new centralized plant with a cooling capacity of 2.5 MW. New centralized cooling plant will annually save 800,000 kWh. The new cooling plant consists of two large air/liquid heat pumps (two 180 kW heat pumps), 9 air-cooled chillers and a number of compressors. According to Shen et al. [24], a heat pump system has been set up to replace a natural gas boiler for the supply of hot water in a medium size hospital in central Taiwan. The total capacity of the pump is 280 kW. This system was built in 2007 and has been run since then. This system could supply steady demand of hot water in temperature and flow rate. Compare to natural gas boiler, heat pump system saving is $90,000 in 7 months and the payback period was 1.8 years.

Heating exchangers, economizers and combustion on burners should be investigated deeply when the heating section of the HVAC systems are focused on. Economizers are used to heat boiler feed water by the using waste heat of the flue gases. The economizer can be considered as a type of heat exchangers. Bujak [25] analyzed heat consumption for heating domestic water in large hospital facilities with over 600 hospital beds. The tests were

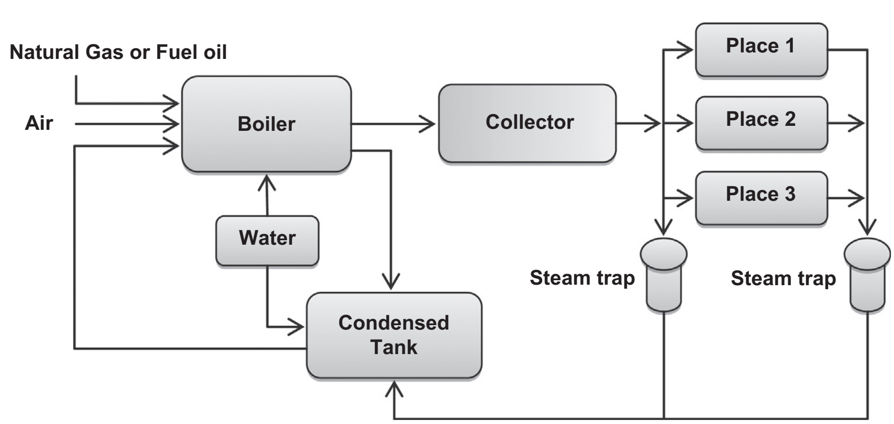


**Fig. 6.** A Typical heating system.

carried out in 2 hospitals: the 715-bed University Hospital and 690-bed Provincial Hospital. The tests were performed over a period of 4 years among the 2005 and 2008 for the first hospital and 2003–2006 for the second hospital. The aim of that study was to analyze the variations and seasonal changes in the heat consumed to produce domestic hot water during the specified time periods. The results of that study have shown the yearly, monthly, daily and hourly consumption of heat for domestic hot water. Daily observations show that the average daily heat consumption on weekdays (Monday–Friday) was always higher than on weekends. The results of that study can be used in the design of new hospital facilities to predict heat consumption. Heat exchangers are used in cooling and heating systems for energy saving and they are generally preferred for heat recovery of heating systems. The working principle of the heat exchanger is to transfer thermal energy between two different ambiences having different temperatures. Generally, external heating source is not used as the heat exchangers. Exhaust, flue gases or hot liquid material which is processed in the production are preferred instead of external heating source. A typical heat exchanger is shown in Fig. 7. If the cold water or other refrigerant material such as freon gas is used instead of steam or hot water, cooling is performed instead of heating. Similarly, energy recovery ventilators (ERVs) are exhausted air energy recovery devices for outdoor ventilation air preconditioning in building the HVAC systems. A sensitivity analysis is used to evaluate the impact of uncertainty of building and HVAC system parameters on the energy savings potential and economics of ERVs in Resole et al. [26]. The results in Resole et al. [26] showed that the ventilation rate has the most significant impact on total HVAC system energy performance. The results also illustrated that an ERV with 75% sensible and 60% latent effectiveness can reduce the peak heating load by 30%, the peak cooling load by 18%, the annual heating energy usage by 40% and the annual cooling energy usage by 8% with a payback period of 2 years.

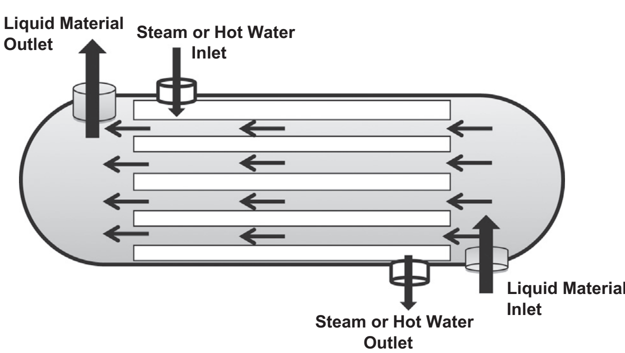


**Fig. 7.** A typical heat exchanger system.

Insulating steam systems with valve insulation jackets is one of the most cost-effective energy-saving measures. Insulation jackets for steam traps can save significant amounts of energy by reducing heat loss and keep the workplace safer.

## 4. VRF/VRV Systems

A multi-split air conditioning system, featuring variable refrigerant flow (VRF) or variable refrigerant volume (VRV) technology, so-called the multi-split VRF/VRV system can satisfy the same needs for the installation of several individual units with less space, because this system consists of one outdoor and multiple indoor units (VRV is a trademark of a leading VRF manufacturer and VRF is a generic term used by all of the VRF manufacturers). Basically, a multi-split VRF system is a refrigerant system that varies the refrigerant flow rate with the help of the variable speed compressor and the electronic expansion valves located in each indoor unit to match the space cooling or heating load in order to maintain the zone air temperature at the indoor set temperature [27]. The schematic view of VRF system is shown in Fig. 8 [28]. Ductless products are fundamentally different from ducted systems in that heat is transferred to or from the space directly by circulating refrigerant to evaporators located near or within the conditioned space. In contrast, conventional systems transfer heat from the space to the refrigerant by circulating air (in ducted systems) or water (in chillers) throughout the building. VRF has larger capacity, and has more complex versions of the ductless multisplit systems with the additional capability of connecting ducted style fan coil units. They are inherently more sophisticated than multisplits, with multiple compressors, many evaporators and complex oil and refrigerant management and control systems. They do not provide ventilation, so a separate ventilation system is necessary. VRF systems have several key benefits, including: installation advantages, design flexibility, maintenance and commissioning, comfort, energy efficiency [29]. Field testing has indicated that this technology can reduce the energy consumption by as much as 30–40% in a year compared to traditional rotary or reciprocating type compressors. VRF technology yields exceptional part-load efficiency. Since most HVAC systems spend most of their operating hours between 30% and 70% of their maximum capacity, where the coefficient of performance (COP) of the VRF is very high, the seasonal energy efficiency of these systems is excellent.

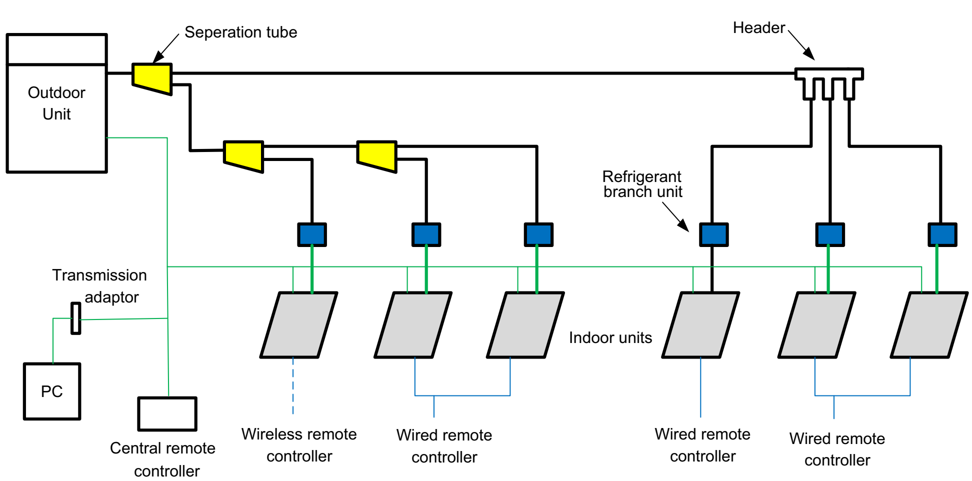


**Fig. 8.** The schematic view of VRF.

VRF system minimizes or eliminates ductwork completely. This reduces the duct losses often estimated to be 10–20% of the total airflow in a ducted system. As with chilled water systems, installed costs for VRF systems are highly variable, project dependent and difficult to pin down. Total installed costs for VRF systems are estimated by some sources to be 5–20% higher than for chilled water systems providing equivalent capacity, but actual costs are highly project dependent [29].

## 5. Cogeneration and trigeneration systems

Cogeneration or CHP (stands for Combined Heat and Power) is the simultaneous generation of electrical and heat energy together with respect to a single fuel type. CHP system is shown schematically as shown in Fig. 9. Cogeneration systems present higher efficiency than the conventional generation methods that produces the electricity and heat separately. The total efficiency of conventional system is close to 60%. The total efficiency of cogeneration system is between 87% and 92%. Natural gas, liquid natural gas and biogas are the most common fuel types used in the CHP systems. In an ordinary cogeneration system, outputs can be classified as exhaust gases, high temperature liquid circuit so called jacket water and low temperature liquid circuit so called after cooler or intercooler output. Exhaust gas is generally more than 500 °C can be evaluated through a steam boiler, hot oil boiler or hot water boiler. The main criteria is the need of the facility where cogeneration system will be installed to select the boiler type. High temperature liquid circuit is connected with a high temperature plate exchanger that transfers its heat to the facility for utilization. For the low temperature liquid circuit, operation principle is the same as jacket water. Meanwhile, vital output is electricity generated in the synchronous generator which is directly coupled to the gas engine. In general, electricity produced in the cogeneration system is cheaper than the grid and the heat outputs are extra gains of the cogeneration principle. CHP (Combined Heat and Power) systems are best suited for some plants (i.e. hospitals, hotels, textile industry, paper factories, food industry, electrolytic copper industry, mining and waste water treatment) where large amount of heat energy (i.e. vapor, hot water or warm water) is required to produce the final product as well as uninterrupted and undistorted electricity generation.

Alexis and Liakos [30] presented a work to investigate whether a Hospital named “Tzaneio”, located in Piraeus, Greece, is a potential candidate for the implementation of a cogeneration system and also to determine the most suitable cogeneration system (electricity and heat). Alternative energy scenarios have been examined that propose the installation of cogeneration units of different power capacity for various profiles of operational hours. A comparative evaluation has been carried out for the selection of the most suitable CHP unit. Alexis and Liakos [30] showed that when the main gas engine (Diesel with natural gas) operates 8000 h/year and the backup unit 5000 h/year, the cogeneration system is most economically profitable. The total annual energy cost has been reduced by 32.4%. The benefit-cost ratio is greater than one, the net present value is positive and the internal rate return for 20 year lifetime of system is 19%. Also there is reduction of annual primary energy consumption by 28%, as well as a significant annual reduction of pollutant emissions.

Silveria et al. [31] aimed an approach for cogeneration plants evaluation based on thermoeconomic functional diagram analysis. The thermo economic optimization method developed has been applied to allow a better configuration of the cogeneration plant associated to a university hospital. Also ecological efficiency has been evaluated. The method was efficient and was contributed for thermo economics modeling and analysis and can be applied to any sort of thermal system, especially those with CHP in thermal parity. Their case study has shown cogeneration alternatives to supply the energy demand of University Hospital of Campinas by using an alternative internal combustion engine. This hospital has 400 rooms, was built on a 60,000 $m^2$ area with 3000 people working there. Around 30% of all electric energy consumed have destined to the air-conditioning system, which is based on steam compression cycle. In the hospital, two different cogeneration technologies were used. The first technology appoints to use the residual heat from exhaust gases to produce steam and the other one uses the same residual heat from exhaust gases to produce cold water in an absorption machine. Four different cases were

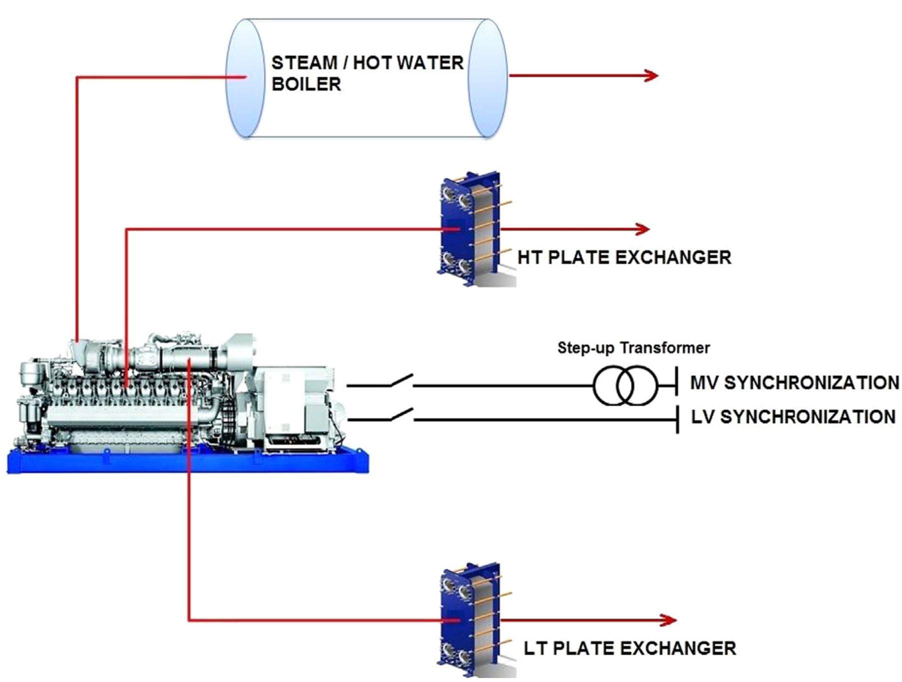


**Fig. 9.** Combined heat and power system.

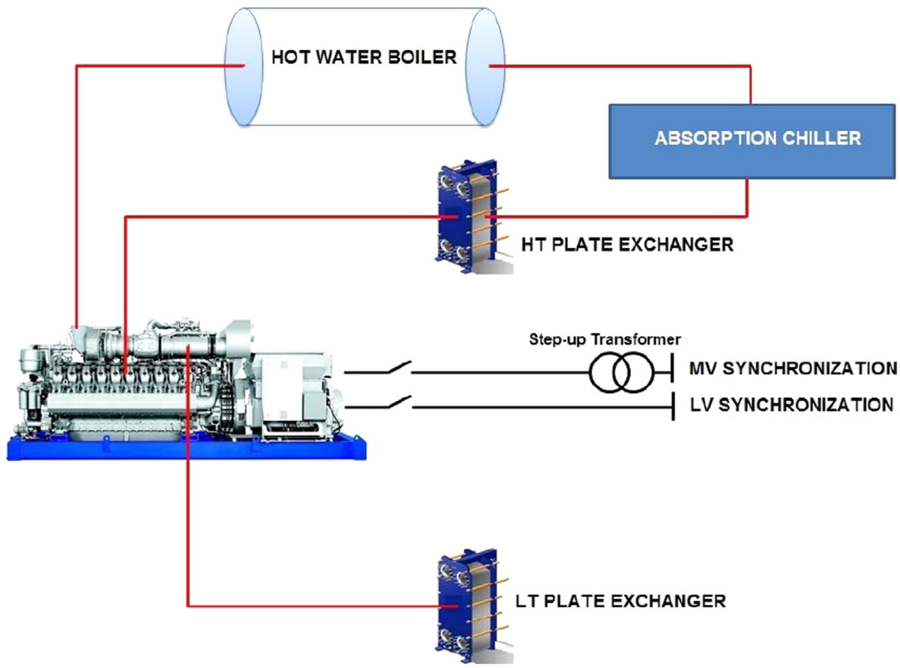


**Fig. 10.** Combined cooling, heating and power system.

defined in their study, The most important case is that, alternative internal combustion engine with natural gas associated to an absorption refrigeration system with direct use of exhaust gases to produce cold water at 7 °C replacing electric chillers, corresponding to a capacity of 700TR (2506 kWc). A double effect (two stages) absorption refrigeration system is jointed (COP = 1.2) to this system. At this case it is possible to achieve a global efficiency around 58% and the payback period is 5 years, is viable with interest rates up to 8.5% with viability guaranteed for a minimum surplus electricity sale price of 0.035 US$/kWh. Gimelli and Muccillo [32], with regard to the S. Paolo Hospital in Naples, solutions that use three gas engines are particularly interesting and are characterized by energy savings of approximately 18%, simple payback period of approximately 4 years and electric power output in the range 225–240 kW for each engine.

Similarly, micro-CHP has been constructed at Mississippi State University (MSU) to show the advantages of these micro scale systems. Research performed by Giffin [33] evaluates the performance of a Micro-CHP system as opposed to a conventional high-efficiency HVAC system that utilizes electrical power from the existing power grid. It was concluded that the combined cycle efficiency from the demonstration site was averaged at 29%. The cooling technology used, an absorption chiller exhibited an average COP of 0.27. The conventional high-efficiency system, during cooling season, had a COP of 4.7. During heating mode, the conventional system had an efficiency of 47% with a fuel.

Trigeneration or CCHP (stands for Combined Cooling, Heat and Power) is the simultaneous production of electricity, heat and cooling with respect to a single fuel type. CCHP system is shown schematically as given in Fig. 10.

Comparing with the conventional generation methods provide the generation of electricity, heat and cooling separately, trigeneration systems present higher efficiency. The total efficiency of trigeneration system is between 85% and 90%. Natural gas, liquid natural gas and biogas are the most common fuel types used in CCHP systems. In an ordinary cogeneration system, outputs can be classified as exhaust gases, high temperature liquid circuit so called jacket water and low temperature liquid circuit so called after cooler or intercooler output. The main difference between cogeneration and trigeneration in the structural design is the utilization of absorption chillers and cooling towers. Exhaust gas is generally more than 500 °C may be evaluated through a hot water boiler that is linked with an absorption chiller and cooling tower in order to obtain cooling from heat. High temperature liquid circuit is also connected with a high temperature plate exchanger that also transfers its heat to the absorption chiller for cooling. For the low temperature liquid circuit, operation principle is the same as jacket water, but heat can be used for the facility like in cogeneration. Meanwhile, vital output is electricity generated in the synchronous generator which is directly coupled to the gas engine. In general, electricity is produced in the trigeneration system is cheaper than the grid and the cooling and heat outputs are extra gains of the trigeneration principle. The CCHP systems are utilized especially in chemistry industry, hospitals, shopping malls and airports where need electricity, cooling and heat together. The most important part of the CCHP is the absorption chiller. Absorption chiller is different from typical chillers as shown in Fig. 11 [15]. The features and differences of absorption chiller can be summarized as replacing of the compressor with pump, absorbing of refrigerant in other liquid, pumping of the liquid to higher pressure, the using of heat to drive refrigerant from solution and no fluocarbons of the system [15].

Research conducted in Pagliarini et al. [34], the feasibility study of a trigeneration plant intended to integrate the existing natural gas fired-boiler central plant serving a 714 bed hospital located in Parma, North of Italy, is presented. The electric load and the heat load for both sanitary hot water and process steam are estimated on an hourly basis from the monitored actual consumption. The space heating and the cooling loads, instead, are computed; on an hourly basis by the building energy software tool TRNSYS, by accounting for the actual climate of the considered location. The energy analysis points out that the primary energy saving index is inadequate for sizing the CHP. The approach based on the second principle of thermodynamics, instead, allows to identify its optimal configuration and size, i.e. CHCP with prime mover overall nominal capacity equal or higher than about 7 MW. The economic analysis shows that the maximum annual money saving occurs with tri-generation at a prime mover overall nominal capacity of about 7 MW with a system simple payback period is of about 1.25 years. Medrano et al. [35] focuses analysis on the main economic, energy-efficiency, and

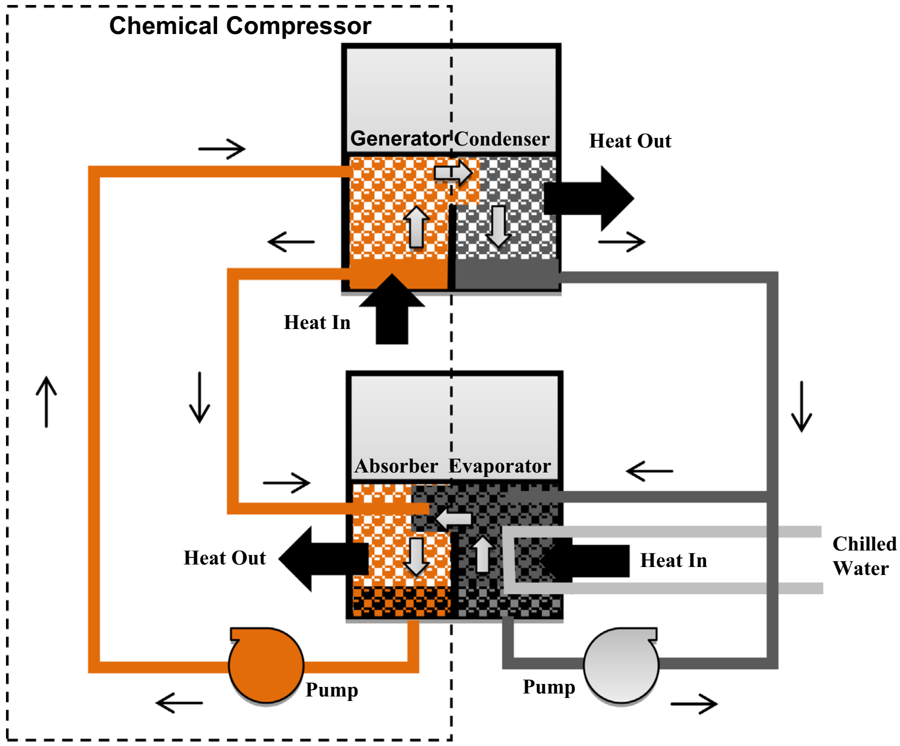


**Fig. 11.** The schematic view of absorption chiller.

environmental impacts of the integration of three types of advanced DG technologies (high-temperature fuel cells, micro-turbines, and photovoltaic solar panels) into four types of representative generic commercial building templates (small office building, medium office building, hospital, and college/school) in southern California (e.g., mild climate), using eQUEST as energy simulation tool.

## 6. Different studies on heating and cooling systems

Energy saving in the HVAC systems can be provided using natural thermal sources as thermal, solar and wind etc. Paksoy et al. [36] designed a new system which uses solar energy in combination with Aquifer Thermal Energy Storage (ATES), that will conserve a major part of the oil and electricity used for heating or cooling the Cukurova University, Balcali Hospital in Adana, Turkey. The purpose of their system is to provide heating and cooling to the hospital by storing solar heat underground in summer and cold in winter. Surface water from the nearby Seyhan Lake was used as the main source of cold energy, ventilation air at the hospital. The system stores solar energy in the form of summer heat and winter cold in an aquifer. Two different well groups are used in the system. In the one of the well groups, cold can be stored and in the other well groups, heat can be stored. In the basic concept groundwater is pumped from one of the well groups and then heated or cooled within the building before being re-injected back into the aquifer in the other well group. At the result of their study, they have predicted that the environmental benefits from this project will be reduction in energy consumption as electricity and fuel oil and replacement of chillers using ozone depleting Freon-12 gas. The savings of fuel oil will be approximately 1000 $m^3$/year and this saving amount will approximately decrease the $CO_2$ emission by 2100 t/year, $SO_x$ by 7 t/year and $NO_x$ by 8 t/year. The replacement of 2 MW of current chillers using Freon-12 will result in a saving of approximately 0.7 t/year of Freon-12.

Another study is also interested in ATES. Vanhoudt et al. [37] report on a monitoring study of a low temperature ATES coupled to reversible heat pumps for heating and cooling a new hospital in near Antwerp–Belgium over a 3 years period. The installation is used for conditioning of the ventilation air. The energy balance shows that the cooling was mainly provided by the direct use for groundwater (81% of the total cooling energy) while also 22% of the heating of the ventilation was provided by direct use of groundwater. The primary energy saving for the acclimatization of the ventilation air reaches 71% as compared to a reference installation composed of gas-fired boilers and compression cooling machines. Furthermore, it was reported that 1280 t $CO_2$ was saved after 3 years of operation.

The performance and economic evaluation of a solar heating and cooling system of a hospital in Crete is studied using the transient simulation program in [38]. The investment cost of the proposed system is quite high. However, the application of the solar air conditioning system has several advantages compared to the conventional air conditioning system. The major benefit is that this technology is environmentally friendly and contributes to a significant decrease of the $CO_2$ emissions which cause the greenhouse effect. Ascione et al. [39] have investigated building coating with isolation materials and its effects on cooling and heating systems. Energy, environmental and economic effects of rehabilitation of building envelopes have been investigated for health care facilities in the Day Hospital of “G. Pascale” Institute in [39]. Two building envelopes have been analyzed: the present building configuration and the designed renovated envelope. Adoption and improvements of effective air-conditioning systems are the main way for improving the use of energy. The retrofit of the building envelope has been evaluated surely convenient also for health care facilities, in terms of energy savings and microclimatic control. However, being the energy requests of health care facilities mainly connected to the thermal-hygrometric transformations of the outdoor air, beyond the energy efficiency of the building envelope, adoption and improvements of effective air-conditioning systems are the main way for

**Table 1**
Energy saving applications in HVAC systems.

| Application details | Energy saving (kWh/year) | Energy savings ($/€ per year) | Simple payback (years) |
|---|---|---|---|
| Arcelor Mittal Indiana Harbor complex completed the installation of a 38 MW CHP system to utilize previously wasted blast furnace gas **(Installation of CHP)** | | $20,000,000 | 1.6 |
| Sikorsky's 10-MW CHP plant (Gas turbine, natural gas), which provides 84% of the facility's electricity needs and 85% of its steam-heating needs **(Installation of CHP)** | | $6,500,000 | < 4 |
| Baptist Medical Center installed a 4.3 MW natural gas turbine. Since the center's recent expansion, the CHP system is capable of meeting 60% of the facility's electrical needs, 80% of its steam needs and 30% of its cooling needs **(Installation of CHP)** | | $800,000 | 6.3 |
| Illinois hospital installed 3.2 MW CHP system **(Installation of CHP)** | | $640,000 | 3.8 |
| Beloit Memorial Hospital installed a 3-MW CHP system which provides the hospital with 1.5 MW of power and the additional 1.5 MW is sold to the local utility, Alliant. In addition, the CHP provides heating, cooling and hot water to the entire facility **(Installation of CHP)** | | $223,000 | 5.4 |
| 1000 kW CHP system operating in a hypothetical hospital within the NIPSCO service area **(Installation of CHP)** | | $187,459 | 3.6 |
| 3.45 MW Cooling, Heating and Power system was placed into operation by Ballard Engineering for Northwest Community Hospital **(Installation of CCHP)** | | $722,000 | 2.9 |
| 2.0 MW CHP Application supplying all of their needed electricity, heating and cooling in Advocate South Suburban Hospital **(Installation of CCHP)** | | $200,000 | 8 |
| In the dairy industry, one facility reported that by installing a system to track its real-time energy usage and emissions, significant opportunities were identified for no-cost behavior modification (staggered boiler start-ups) and low-cost energy savings projects **(Compressed air, boiler system and refrigeration system improvements)**. | 2,800,000 | | 1.2 |
| At the J.R. Simplot Company potato processing facility in Caldwell, Idaho, the installation of new burners equipped with process controls and a flue gas trim system led to significant annual savings in natural gas consumption. Natural gas consumption was reduced by 7.5% **(Installation of new burners)** | | $279,000 | 1.16 |
| At the Odwalla Juice Company's facility in Dinuva, California, an economizer was installed. **(Installation of new economizer)** | | $21,000 | 0.83 |
| A Unilever Canada margarine plant installed a condensing economizer **(Installation of condensing economizer)** | | $378,000 | 1.32 |
| Green Giant of Canada, a manufacturer of frozen and canned vegetables, installed a shell and tube heat exchanger to recover heat from boiler blow down **(Installation of heat exchanger)** | | $1500 | 2 |
| At a Land O'Lakes dairy facility in Tulare, California, a US DOE sponsored energy assessment estimated that implementing a steam trap maintenance program **(Steam trap maintenance)** | | $278,000 | < 0.33 |
| Steam Traps Preventive Maintenance in Hoboken University Medical Center **(Steam trap maintenance)** | | $6840 | 1.8 |
| US based food processing facility predicted that the installation of a flash steam recovery system (**Installation of a flash steam recovery system)** | | $29,000 | < 1.8 |
| Stahlbush Island Farms, a grower, canner and freezer of fruits and vegetables in Corvalis Oregon, installed timers to cycle the evaporator fans of its cold storage unit **(Installation of a timer)** | 133,000 | $4500 | 0.25 |
| Solar air heating systems, such as Solar wall, use conventional steel siding painted black to absorb solar radiation for insulation. Ford Motor Company's Chicago Stamping plant turned the south wall of its plant into a huge solar collector **(Installation of a solar air heating systems)** | | $300,000 | < 3 |
| The A. Lassonde Company replaced its old electric water heating system used for pasteurization with a pair of 880 kW natural gas-fired compact immersion tube water heating units. **(Installation of a natural gas-fired water heating units)** | | $18,100 | < 2 |
| Existing HVAC system consisted of individual AHU on each floor equipped with DX cooling air handling units rejecting heat to condenser water loop/cooling tower system. The system upgrade consisted of converting the DX cooling to central plant chilled water cooling by changing out the AHU coils and adding efficient VSD centrifugal chillers to the system. **(Converting the DX cooling to central plant chilled water cooling)** | 2,900,000 | | 2.7 |
| Chillers replacement in a public Portuguese hospital. Existing chiller: 375 kW, COP 2.53 New chiller: 317 kW, COP 3 **(Chiller replacement project)** | 876,960 | €98,414 | 3.8 |
| Palm Beach Hotel increases cooling system efficiency by replacing old chillers of 300 kW with a higher COP new Chiller of 340 kW. **(Chiller replacement project)** | | $23,760 | 3.3 |
| Chillers replacement in a New York Hospital Queens. Super-efficient electric chiller bonus by exceeding standard energy efficiency criteria by at least 2% at full load and by at least 12% at part load. **(Chiller replacement project)** | 175,200 | $33,304 | 2.8 |
| Four seasons hotel in Sydney replaced one of the site's three older chillers and a high efficiency water-cooled model and old 3-cell wooden cooling tower with two new fiberglass towers. **(Chiller and cooling tower replacement)** | 721,559 | $79,313 | 5.4 |
| Design and installation of new efficient chiller plant including the use of a "free cooling" plate and frame heat exchanger in Cabot's facility. In addition, several other efficiency improvements were implemented including variable speed drives on the primary and secondary chilled water pumps, condenser water pumps and root top units. **(Installation of new efficient chiller plant)** | 1,200,000 | $300,000 | > 4 |
| Harvard University in Cambridge, Massachusetts Installed new high efficiency central chiller, converted air systems to VAV, installed DDC EMS and installed VFDs on pumps and fans. **(installation of new efficient chiller plant)** | 2,100,000 | | 3.3 |
| Carney Hospital in Dorchester, Massachusetts installed new high efficiency chillers under VFD control, modified AHU VFD, installed additional EMS controls, converted fixtures to super T-8 technology, modified VAV system in office building. **(Installation of new efficient chiller plant)** | 2,711,000 | $470,400 | 3 |
| Colonnade Hotel in Boston, Massachusetts installed 25 -ton frictionless centrifugal chiller, replaced standard-efficiency motors with ECM motors, installed new BAS, modified AHUs, installed efficient lighting with occupancy controls in various areas. **(Installation of new efficient chiller plant)** | 1,259,490 | $255,693 | 2.3 |
| The standard ASHRAE chillers at Emory University Winship Cancer Institute was replaced with high efficiency one **(installation of new efficient chiller)** | 920,364 | $46,018 | 2.17 |
| Retrofit/Replace 100% Outside Air AHUs with Re-circulating AHUs at Hoboken University Medical Center **(Capability of re-circulating air)** | | $41,740 | 3.2 |

**Table 1** (*continued*)

| Application details | Energy saving (kWh/year) | Energy savings ($/€ per year) | Simple payback (years) |
|---|---|---|---|
| Air curtain application by TMI LLC company, a minimum of 70% of the heat from being lost is saved using air curtain. **(Air curtain application)** | | $ 3066 | 1.2 |
| Wrap-around valve insulation jackets will be fitted to all uninsulated valves in the London School of Hygiene & Tropical Medicine **(Valve insulation jacket application)** | 35,080 | $2555 | 1.5 |
| Steam-valve insulation is being added throughout the campus utility, System. 2000 removable, reusable insulation covers are being added throughout the UC's Uptown Campus in the University of Cincinnati. **(Steam-valve insulation)** | | $500,000 | 0.6 |

improving the use of energy. Usefulness of cogeneration and trigeneration systems combined, depending on specific peculiarities, to adsorption dehumidifiers and/or to absorption chillers is concluded in [39].

Practical applications of improving energy efficiency and saving in the HVAC systems are summarized in Table 1 [40–45].

## 7. Conclusions

In this study, findings of the previous papers and practical implementations on the HVAC systems at the hospitals are summarized. The most important conclusions of this paper can be outlined as follows:

- According to international standards, the desirable indoor temperature is usually 20–24 °C and the recommended levels of indoor relative humidity are 30–60%. Most standards recommend 20 ACH in a room [5].
- The heart of the cooling unit in HVAC systems is chiller and the heart of the heating unit in HVAC system is boiler. According to condenser type, chillers can be classified as water cooled and air cooled. 69% of chillers are air cooled non-ducted, 25% of chillers are water cooled, 4% of them are water cooled with ducted and 2% of them are conderserless [16]. Similarly, 65% of boilers are gas fired, 28% of the boilers are oil fired and %7 of the boilers are electric [23].
- Energy usage of the cooling systems with water cooled are 69% of energy in chiller, 11% of energy in condenser water pump, 11% of energy of chiller water pump and 9% of energy in cooling tower fans.
- Conventional thinking has been that water cooled chillers are more efficient than air cooled chillers. If only compressor costs are considered, this may be true. However, according Thermal Care, Inc., total annual savings of 58% can be achieved with air-cooled chillers using state-of-the-art technology with centrifugal compressors and VSDs.
- With the propoer selection of the efficient components and controls at the water cooled systems, energy used by chiller plants can be decreased 30–50% less energy than the system designed [16]. Similarly, the most efficient boilers are gas fired. The efficiency of energy efficient gas-fired boiler systems is between 85% and 95% [23]. Payback period of chiller replacement is between 3 and 3.5 years depending on the chiller size and overall system efficiency.
- VRV/VRF type of HVAC has very high COP. The seasonal energy efficiency of this system is excellent. According to studies performed, total installed cost of VRF is estimated 5–20% higher than for chilled water systems. But VRF systems are more efficient then the chilled water systems at the same time [29].
- Heat exchangers should be used for the heat recovery in the heating systems. When the new heat exchanger is added into the system, the payback period is expected to be between 1 and 2 years.
- Especially, at the building using the natural gas, cogeneration or trigeneration systems can be used to increase the energy efficiency. The total efficiency of conventional system is close to 60% and the total efficiency of cogeneration system is between 87% and 92%. Trigeneration systems are more efficient than the cogeneration systems. Trigeneration plants can reach system efficiencies between 85% and 90%. Depending on the project type and the size of projects, the efficiency percentages of CHP or CCHP can be different. When new CHP or CCHP is installed, the average payback period will be between 2.5 and 5 years.
- Aquifer systems can be used as different heating and ventilating system to save energy alternatively. Other alternative methods should be analyzed in detail and then if payback period is between 2 and 3 years then, they should be absolutely applied.
- All leakages should be prevented by using isolation materials and all joints points should be tightly sealed.
- Regular maintenance should be performed and especially all filters in the HVAC systems should be cleaned periodically. Maintenance personals should join the vocational training programs and take the required certifications. Regular maintenance payback period will be about 0.5–2 years.
- The layout of objects in room is important for HVAC systems. Objects near the radiators or blowers of fan should be moved to the free space.
- Hospitals should be divided to zones according to conditioning and different AHUs should be used for every zone.
- Especially drug rooms and critical places should be controlled by devices which measure ambient humidity, temperature and ACH values for 24/7.
- Internal auditors should check the all consumption bills such as electricity and fuel oil. In addition, they should also check hospital units according to quality standards.
- The hospital's services operate 365 days a year, 24 hours a day. It is normal that average daily heat consumption on weekdays is always higher than on weekends because fewer employees work on weekends. This point should not be ignored and the sources of heating system should be arranged again.
- VSDs should be used in HVAC components such as pump motors, VAV fans and cooling tower motors. In a pump system with VSD, when the speed of pump decreases to 10%, the power reduction will be 27% that satisfy the energy saving.

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